Evolution of the Energetiq Electrodeless Z-Pinch™ EUV Source:

Control of Plasma Length

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Outline

- The Electrodeless Z-Pinch™ – overview of basic physics
- What determines plasma length?
  - Some early history…
  - The EQ-10 metrology source as a product.
- EQ-10 design is constrained by physics. Try to break constraints by introducing new physics – axial magnetic fields.
- Unexpected results….
- Conclusion

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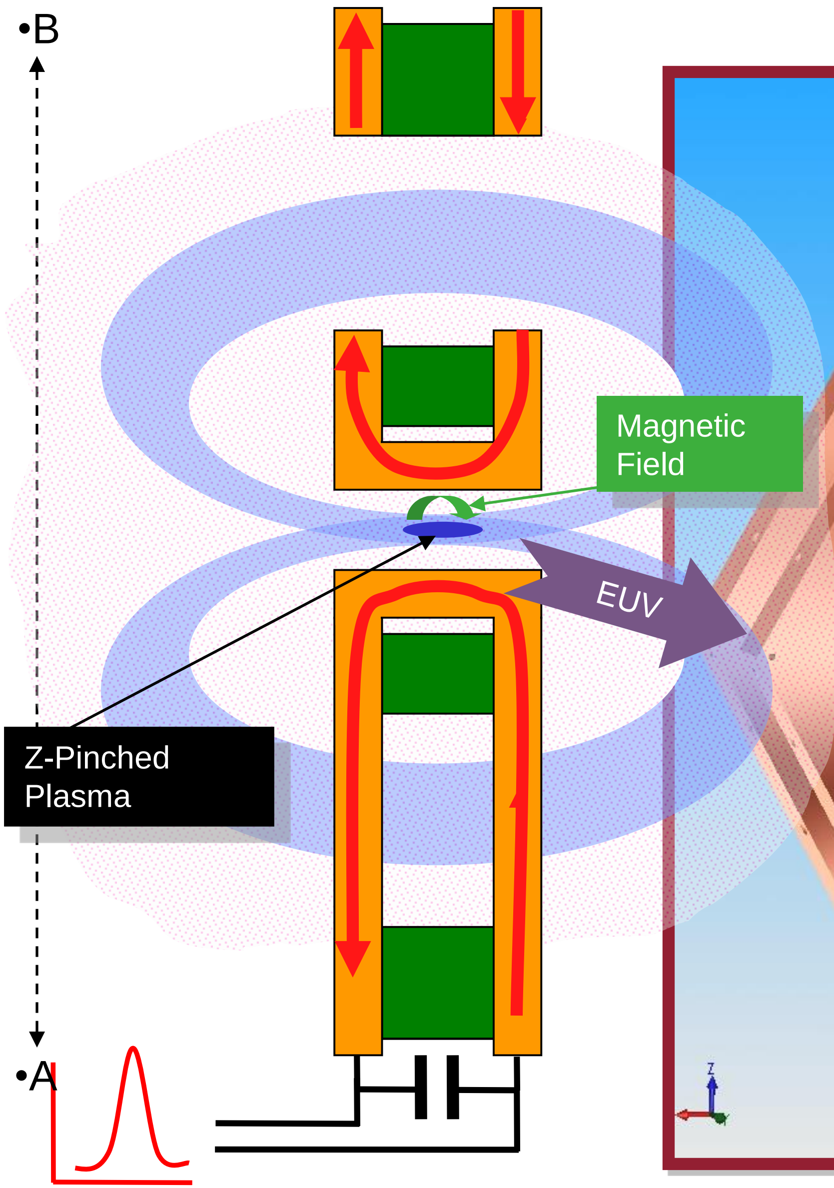
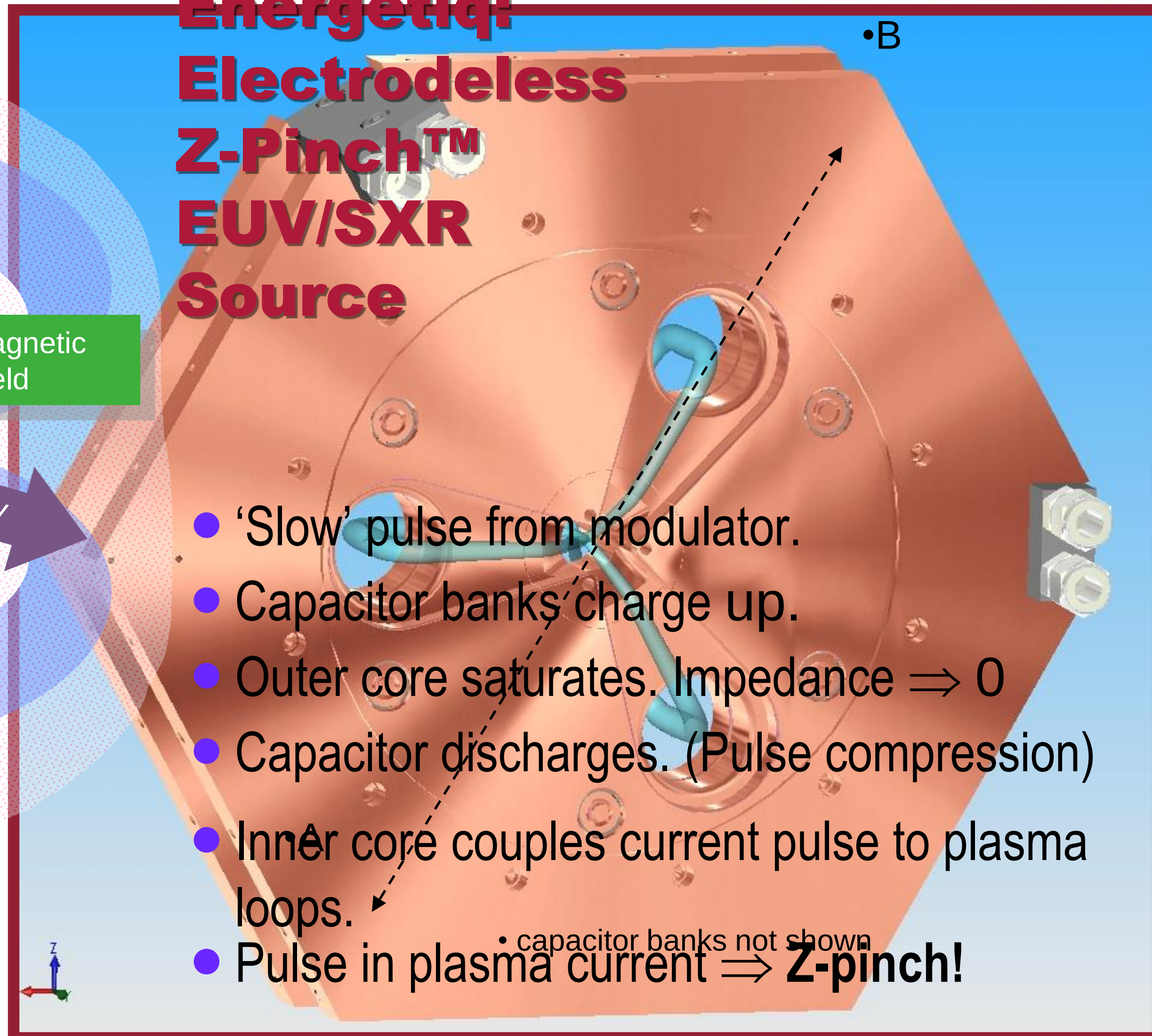
Electrodeless Z-Pinch™ EUV Source

- Our group had decades of experience with inductive plasmas
  - Controlled fusion program (U. Wisconsin, MIT Plasma Fusion Center)
  - Industrial applications (Atomic Fluorine and other radicals)
- Advances in magnetic materials –(fast switching cores) and power electronics enabled a new device to be designed.
- Energetiq was founded to develop and commercialize this device.

Energetiq: Electrodeless Z-Pinch™ EUV/SXR Source



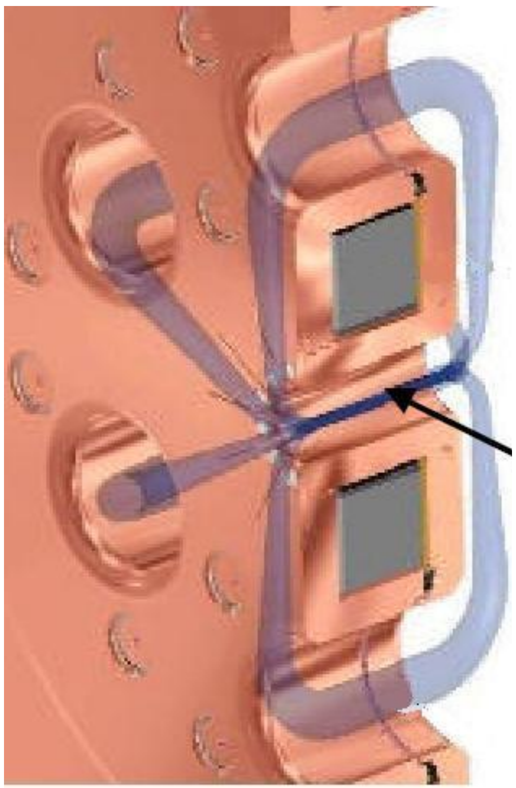


- ‘Slow’ pulse from modulator.
- Capacitor banks charge up.
- Outer core saturates. Impedance $\Rightarrow$ 0
- Capacitor discharges. (Pulse compression)
- Inner core couples current pulse to plasma loops.
- Pulse in plasma current $\Rightarrow$ **Z-pinch!**

Primary topic – how do we control plasma length in the Electrodeless Z-pinch? (including some history…)

- Standard Z-pinch has electrodes –
- Forces plasma to have a specific maximum length – can't be longer than distance between electrodes, because current flows only there
- A small (short) EUV emission region simplifies optics design, saves wasted light/power…
- Electrode-less pinch has current flow over long region. How to control plasma length?

To control plasma length, control plasma radius…



- Total voltage around plasma loop determined by d/dt of magnetic flux in core. Current is constant around length of loop, so…
- Electric field distribution along plasma loop determined by plasma impedance. Current is ramping, so inductance/length is key.
- Inductance/unit length $dL/dl \sim \log(1/r)$ - $r \to$ zero, dL/dl approaches infinity.
- Most of the applied voltage appears across the narrowest plasma cross-section. Nearly all the pulse energy is dissipated there.
- To control plasma length, control the radius.

Z-pinch Snowplow Model...

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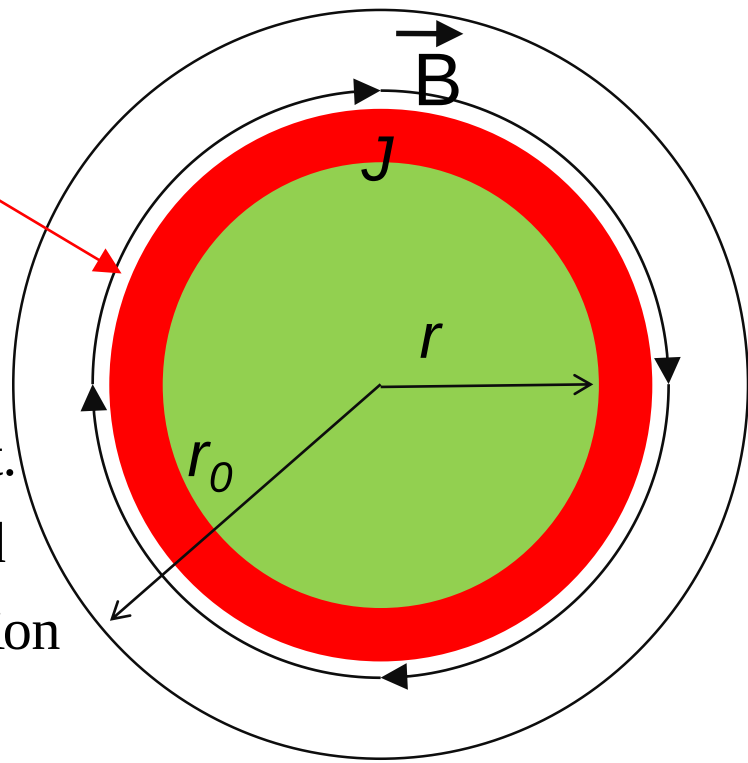
$$d/dt\left[\pi\underbrace{\rho(r_0^2 - r^2)}dr/dt\right] = -\mu_0 I^2(t)/(4\pi r)$$

$$t = r_0 \left(\frac{4\pi^2\rho}{\mu_o I^2 \omega^2}\right)^{(1/4)}$$



I : Current, assumed sinusouidal, frequency ω

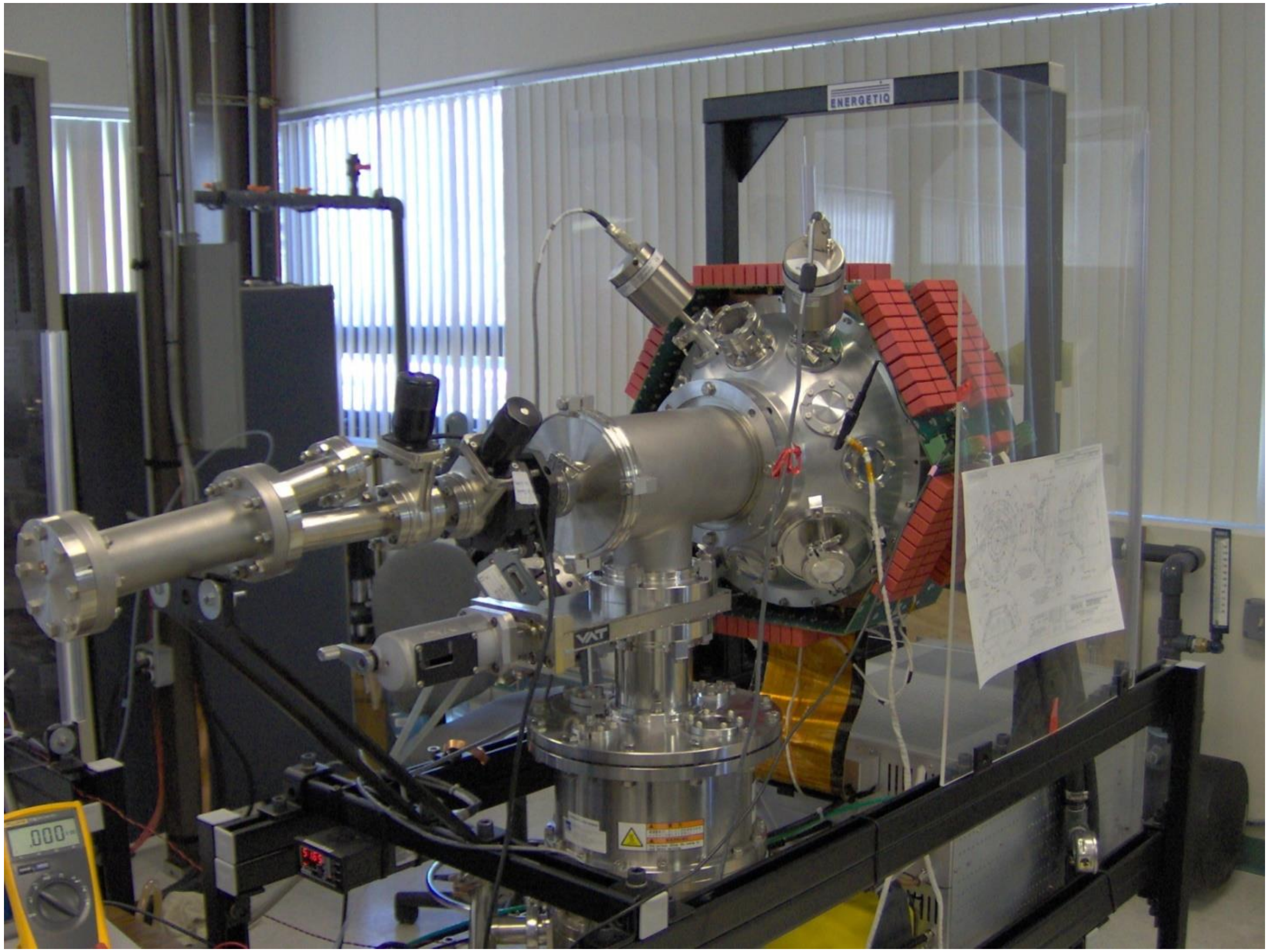
t : Characteristic time. Pinch goes to zero at 3/2 t.

$t \approx r_0$, so average pinch velocity does not depend on initial radius. Pinch will occur at axial location where initial (unpinched) r_0 is a minimum.

- See Sheshadri, Fundamentals of Plasma Physics, or Krall and Trivelpiece, Principals of Plasma Physics

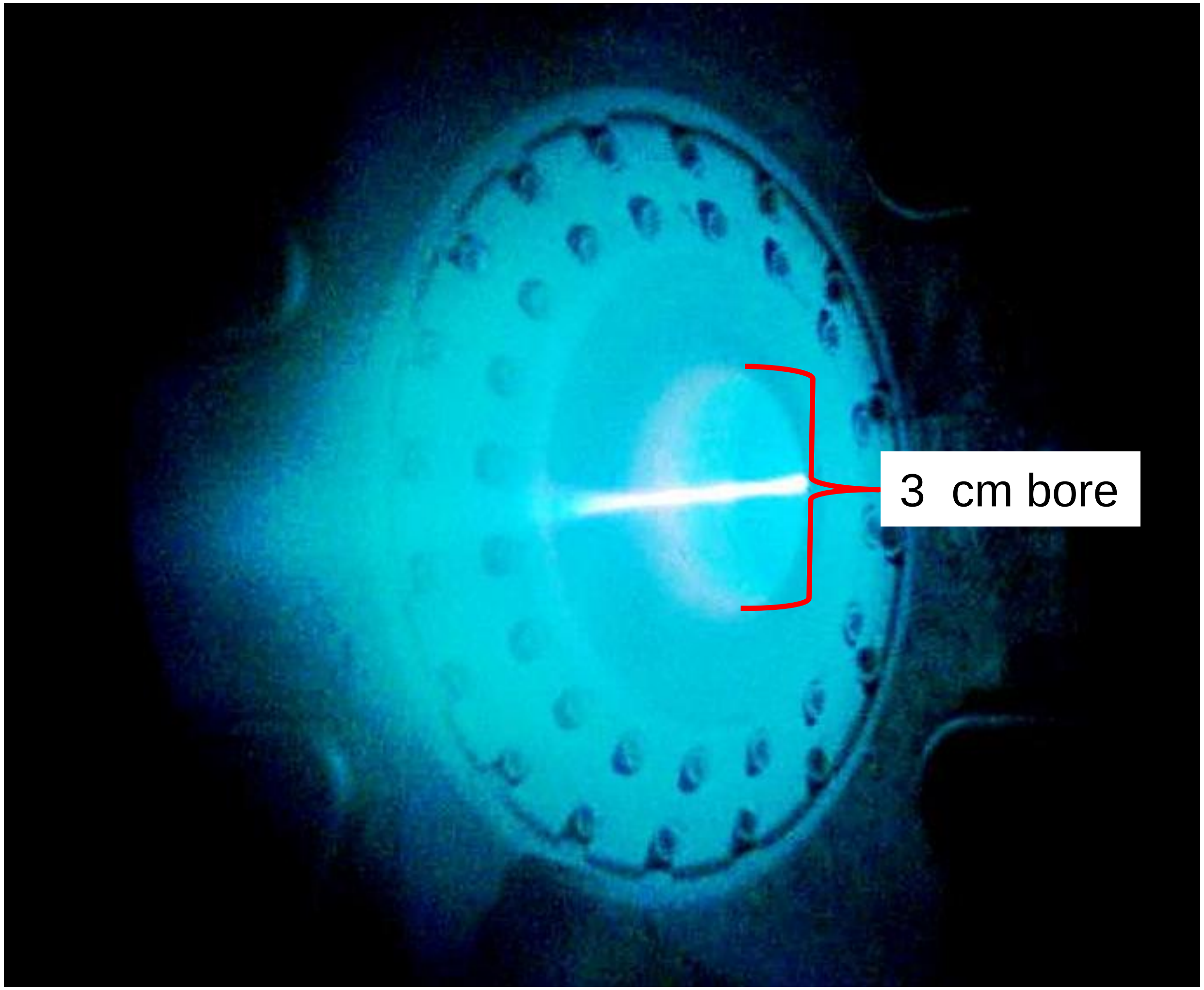
Early data – first attempts to control source size

- Prototype source development, 2004-2005



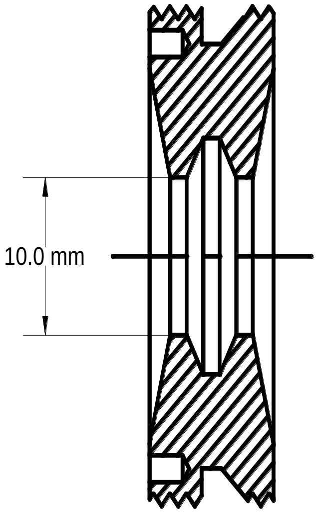
First experiments had very large “bore”

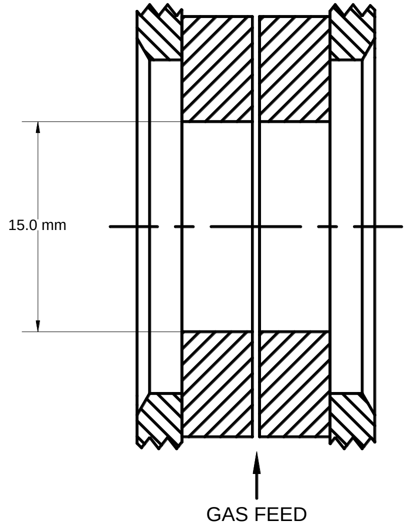
- No attempt to control plasma length –
- ~ 8 cm long plasma!

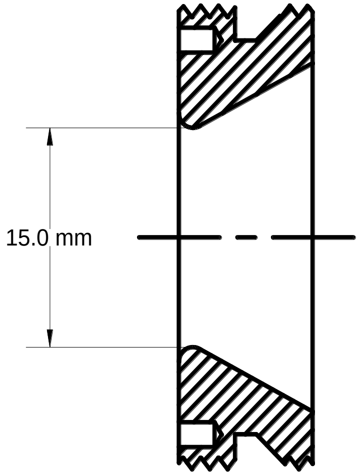


A program to investigate plasma size, lifetime issues…

- Various bore geometries and materials tested – examples…







Silicon Carbide, specific geometry

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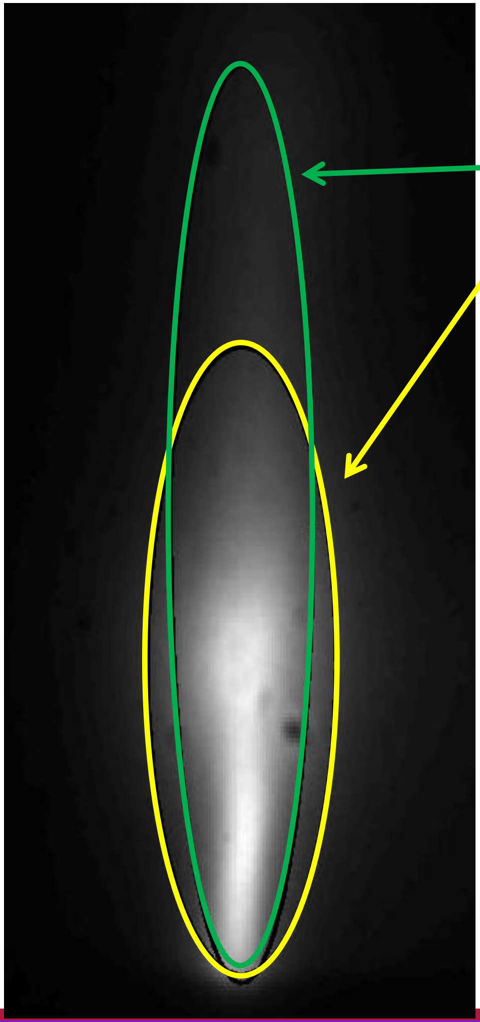
Material	Length	Diam	Geometry	Pwr(2pi)	Etendue	Fwhm l	Fwhm d
POCO Graphite	0.96	15	offset	31.36	6.9005	7.3859	0.836
POCO Graphite	0.96	10	recurve	4.95		3.1	2.3
Oriented Graphite	1.5	10	washer	26.25	6.6421	7.4551	0.7994
Oriented Graphite	1.5	15	washer	25.67	7.714	5.5958	1.187
Oriented Graphite	4.5	10	3 washers	25.91	2.543	3.867	0.5815
Oriented Graphite	3	15	washer	33.08	5.3696	6.6506	0.724
Silicon Carbide	5	15	washer	32.72	3.6709	4.8996	0.6661
Silicon Carbide	3	15	2 washers	32.15	5.5233	5.2937	0.9145
Silicon Carbide	3	15	2 washers	10.02	5.7322	5.4921	0.917
Silicon Carbide	3	15	2 washers	9.74	7.2776	6.251	1.0242

Effect of collector geometry



- Identical etendue… different collection angles
- 45 degree collector
- 54 degree collector
- Intensity distribution, collector design, optics are all coupled.
- Etendue specification is only a start. Collection angle (first optic) drives optics and beamline design.

•Derra, Guenther H., and Wolfgang Singer. "Collection efficiency of EUV sources." In *Microlithography 2003*, pp. 728-741. International Society for Optics and Photonics, 2003.

Learning from prototype → commercial metrology source… key points

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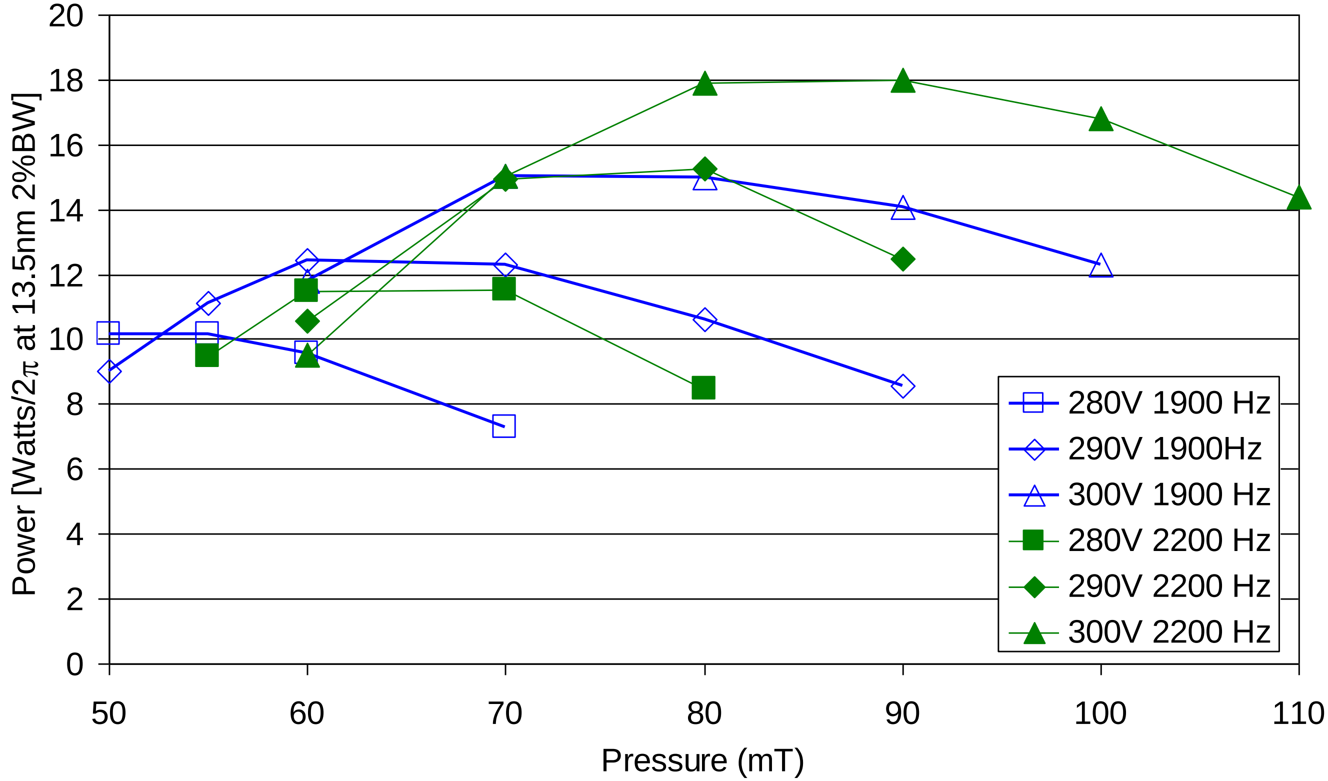
- Plasma size drives optical design process –
  - Pick a geometry and stick with it…
- A 25 eV Xenon plasma is a fierce environment for materials
  - Lifetime of plasma-facing components determine maintenance interval.
  - Resistance to sputtering is key.
- For metrology, smaller etendue is acceptable.
  - Long plasmas, small collection angles easier to manage
    - More power and brightness from source
    - Simpler optics in instrument.
    - Smaller foils, mitigation structures

Xenon source performance: EUV power

- Power in Watts, into 2π steradians , within 2% BW of 13.5 nm :



- Parameters: input voltage and pulse rate. Input power here ~ 4 – 5 kW
- Input pulse energy increases with input DC voltage

Stability in Plasma Position

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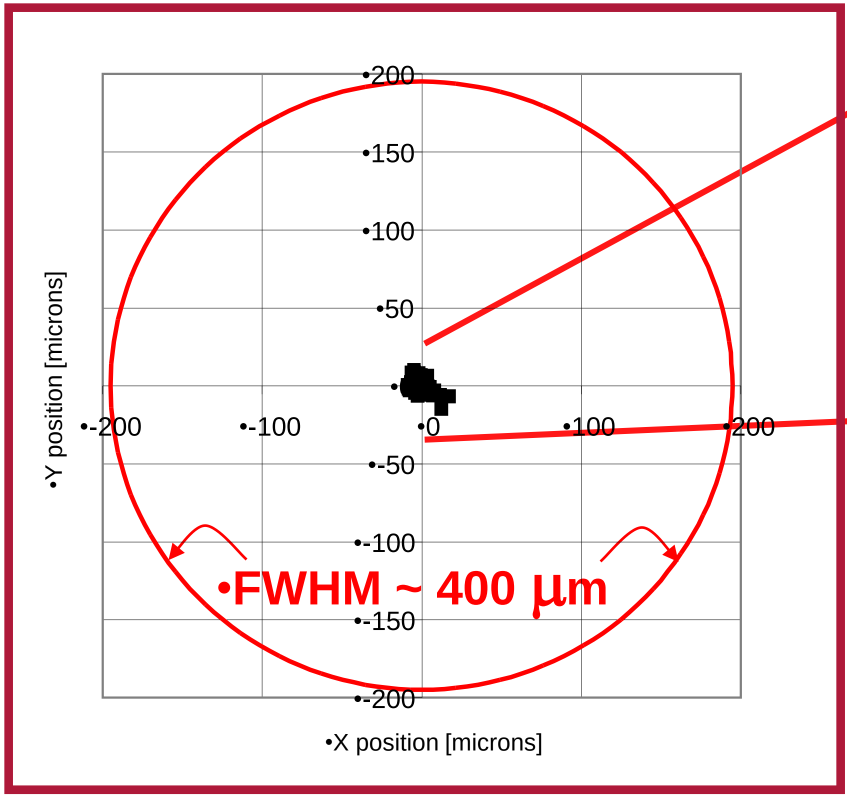
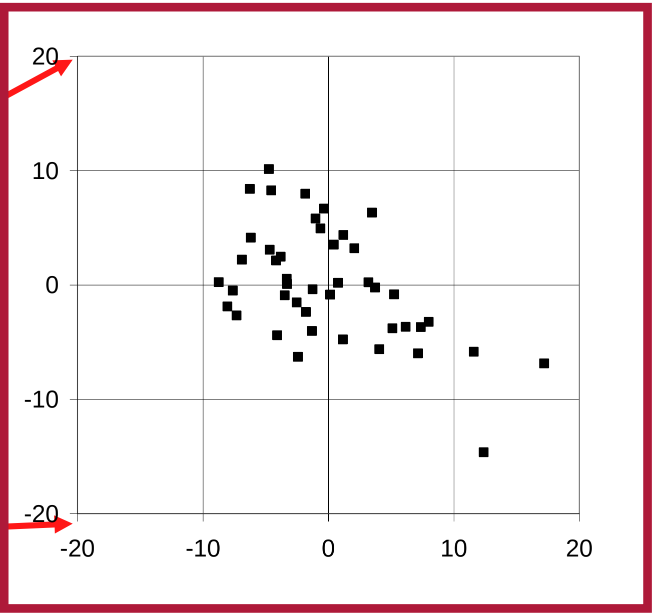
- Image recorded at 13.5 nm, once an hour for over 300 million pulses (~44hours) of continuous operation. Position then extracted from images:
  - Position: σ_x= 5.8 µm and σ_y= 5.0 µm

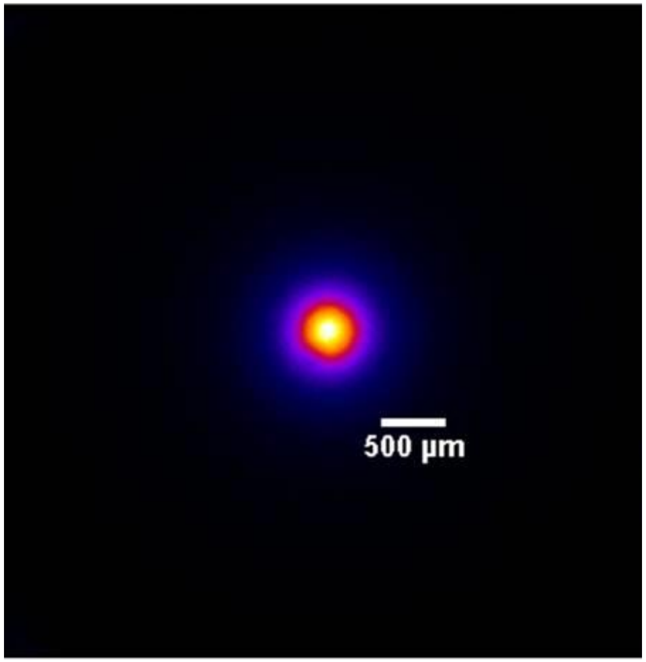


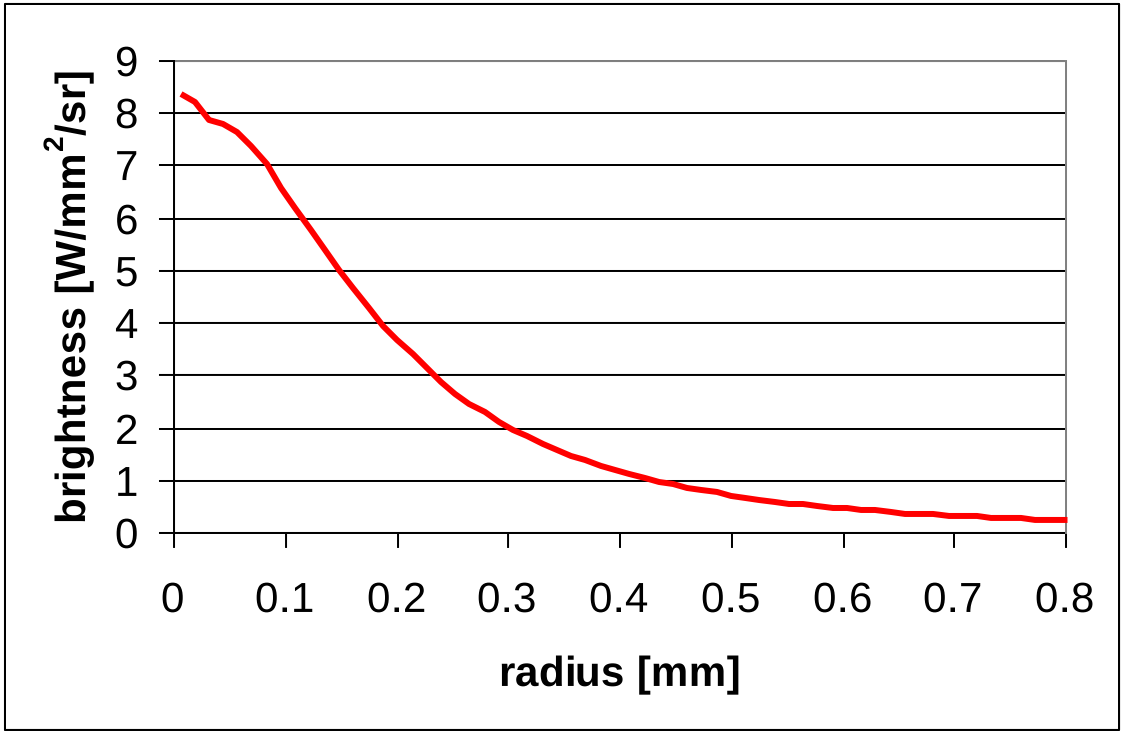


- This is open-loop stability: No feedback!

Xenon Source Performance: EUV brightness

- Power plus imaging measurement
- Typical fwhm ~ 400 microns
- Profile is not Gaussian





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Sample of Current Installations (~ 20 worldwide)

•EUV Technology Outgassing Tool Installed at IMEC

- Flood Exposure system installed at Osaka University (Tagawa Lab)

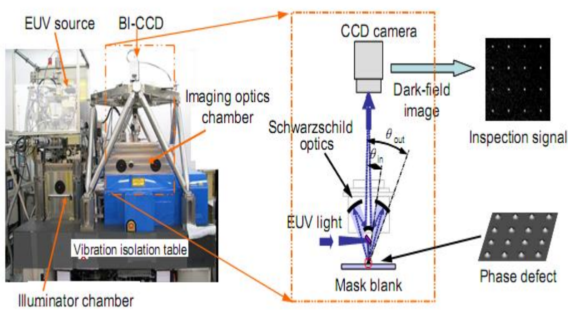


Figure 2 Actinic mask blank inspection tool built at MIRAI-Selete clean room and concept of its inspection optics using dark-field imaging.

•Actinic Mask Inspection Tool at Selete

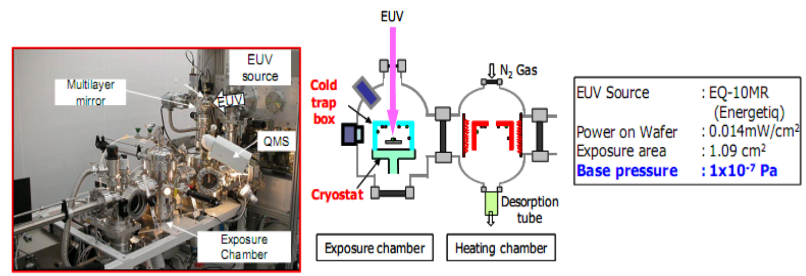
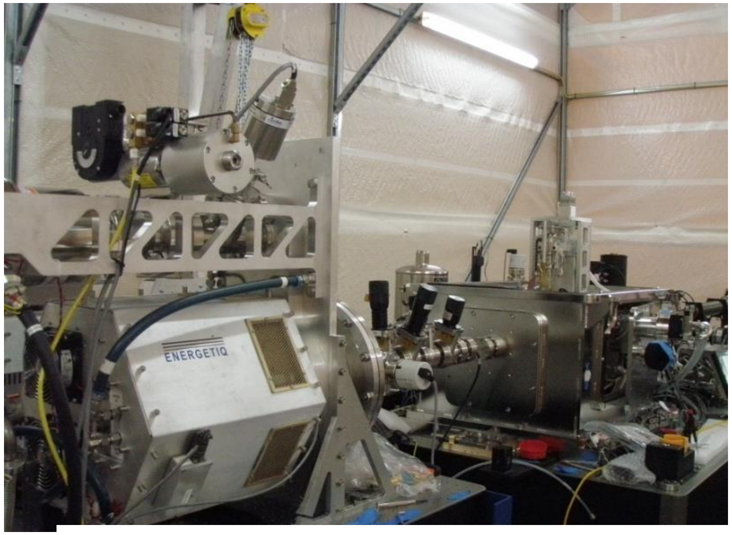


Figure 2. Photograph and schematic of resist outgassing evaluation tool used for GC-MS method.

•LithoTech Outgassing Tool installed at Selete

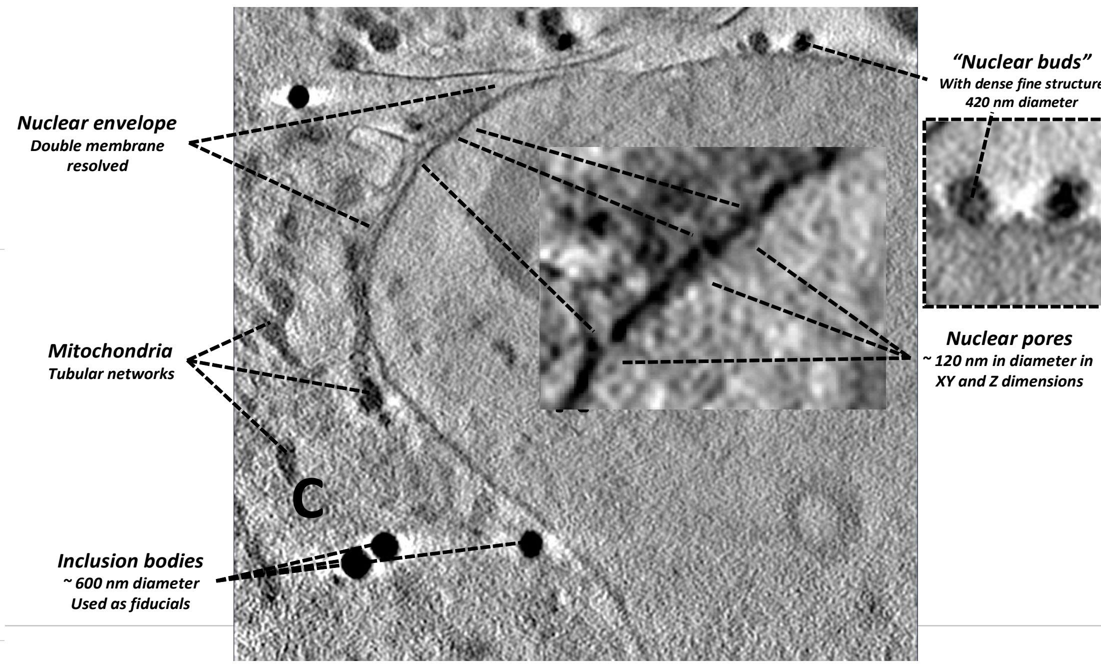
Cryo-tomography with EQ-10 at Diamond Synchrotron, England



Preliminary Laboratory-source Results (Diamond) courtesy Liz Duke and Colleagues

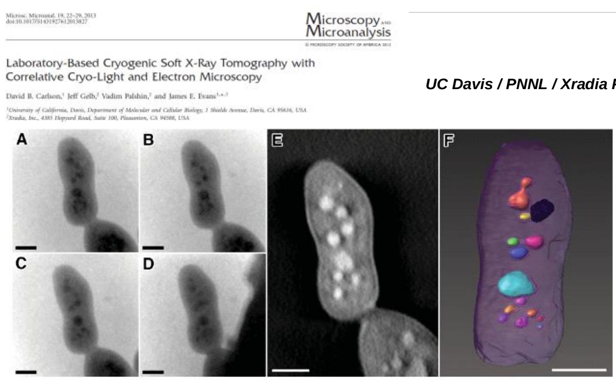
Nuclear / perinuclear region of a HeLa cell

Xradia 825 Ultra



UltraXRM-L220c Development and Correlative

UC Davis / PNNL / Xradia Paper



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Laboratory-Based Cryogenic Soft X-Ray Tomography with Correlative Cryo-Light and Electron Microscopy

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Carlson, et al, Microscopy and Microanalysis, 19 (2013)

The story so far…

- Initial experiments (first prototype) gave long plasmas… too long
- We exploited the connections between geometric boundary conditions and plasma inductance to develop a robust product, appropriate for many metrology and infrastructure applications.
- Within the physics and engineering constraints set by the existing device, we were near an optimum.
- To get higher performance, need to add some new physics.
- **Consider an axial magnetic field, varying along the z-pinch axis.**
- **By changing the radial pressure balance, can this influence plasma length?**

Add an axially varying B-field; B(z) – use the z-pinch itself to compress an initial static field

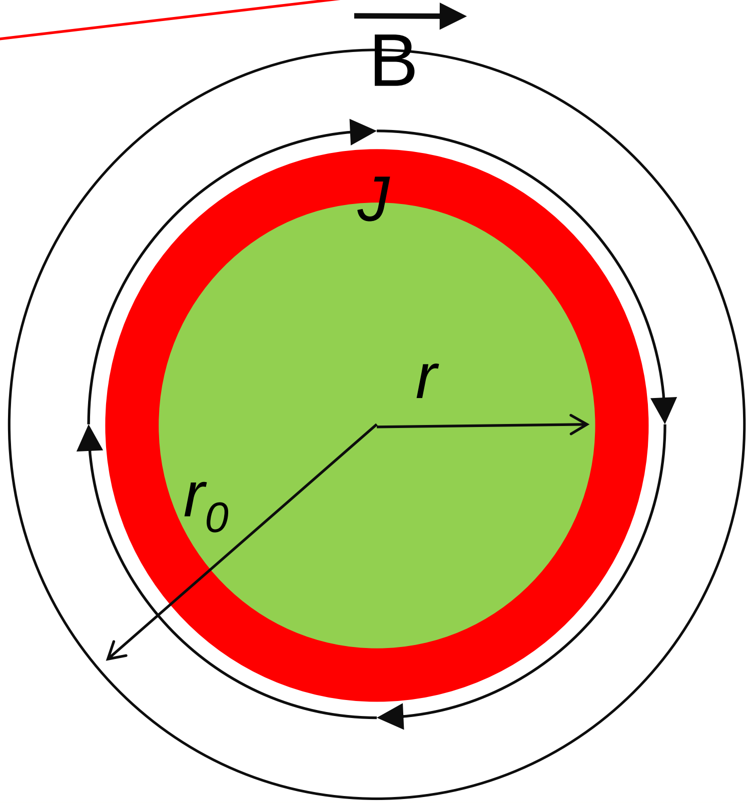
$$d/dt\left[\pi\rho(r_0^2 - r^2)dr/dt\right] = -\mu_0 I^2(t)/(4\pi r) + P_m(2\pi r)$$

$$P_m = B(z)^2/(2\mu_0)$$

Conductive plasma shell will compress an initial field

$$\frac{B_0(z)^2 r_0^4}{r^3}\frac{\pi}{\mu_0}$$

Geometric compression of initial weaker field produces tesla-size fields as pinch progresses



Adding an axial magnetic field...

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- We introduce another pressure against which the pinch force must act.

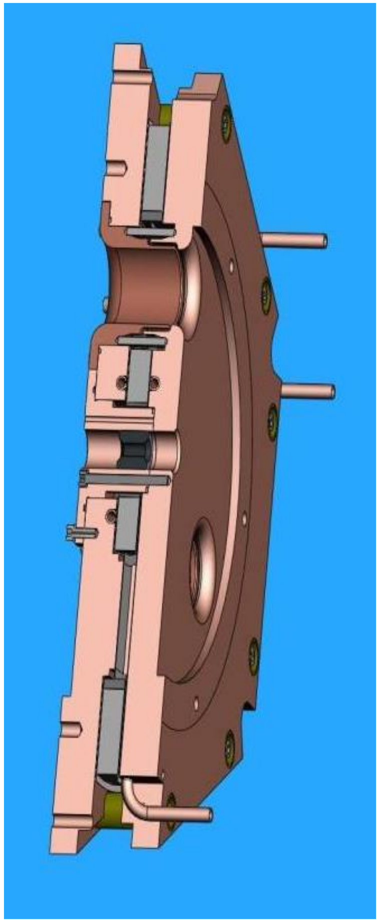
$$P_m = B(z)^2 / (2\mu_0)$$

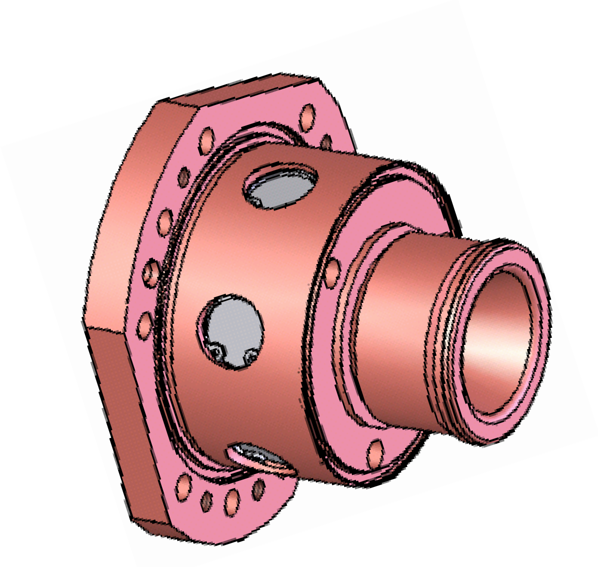
  - The axial field will be compressed and magnified by the collapsing, conductive plasma
  - Pressure ~ B^2, B ~ 1/R^2, so magnetic pressure resisting the pinch ~ 1/R^4
- By tailoring B(z), we can control this axial pressure, thus controlling both the position and axial length of the plasma.
- Make the B-field zero at the center of the bore.
  - **A spindle cusp**
  - Need field to be “significant” at the ends of the bore .
  - How much field?

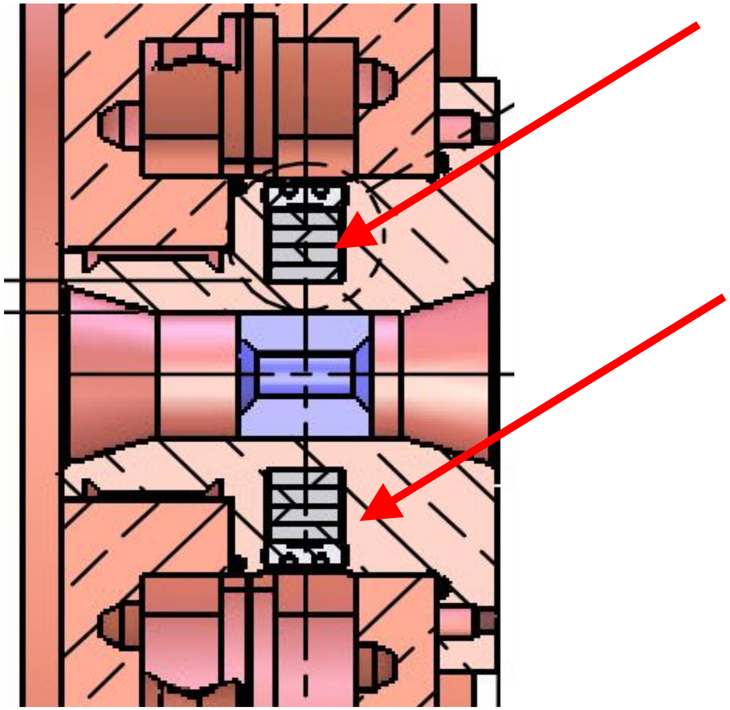
Three estimates of required field

- Typically operate about 100 mT neutral pressure.. ~ 13 Pa
  - Solve for B in Tesla - ~ .006 T, or **60 G.**
- Plasma pressure - density 1.e18, Te 25 eV, nkt ~ 4.e6 Pa
  - B=3T, compressed
  - Compression increases B by factor of (6 mm / 0.4 mm)^2 = 225
  - Initial B .014 T, or **140 G**
- Plasma self field, at compression (5000 A, r=0.2 mm), 5 T
  - Take credit for compression, as in 2) – result is comparable
  - **Bz = B_theta is almost certainly way too much field.**
  - **Conclude – need 100 – 200 G field to affect pinch behavior.**

No space or access for coils… use permanent magnets



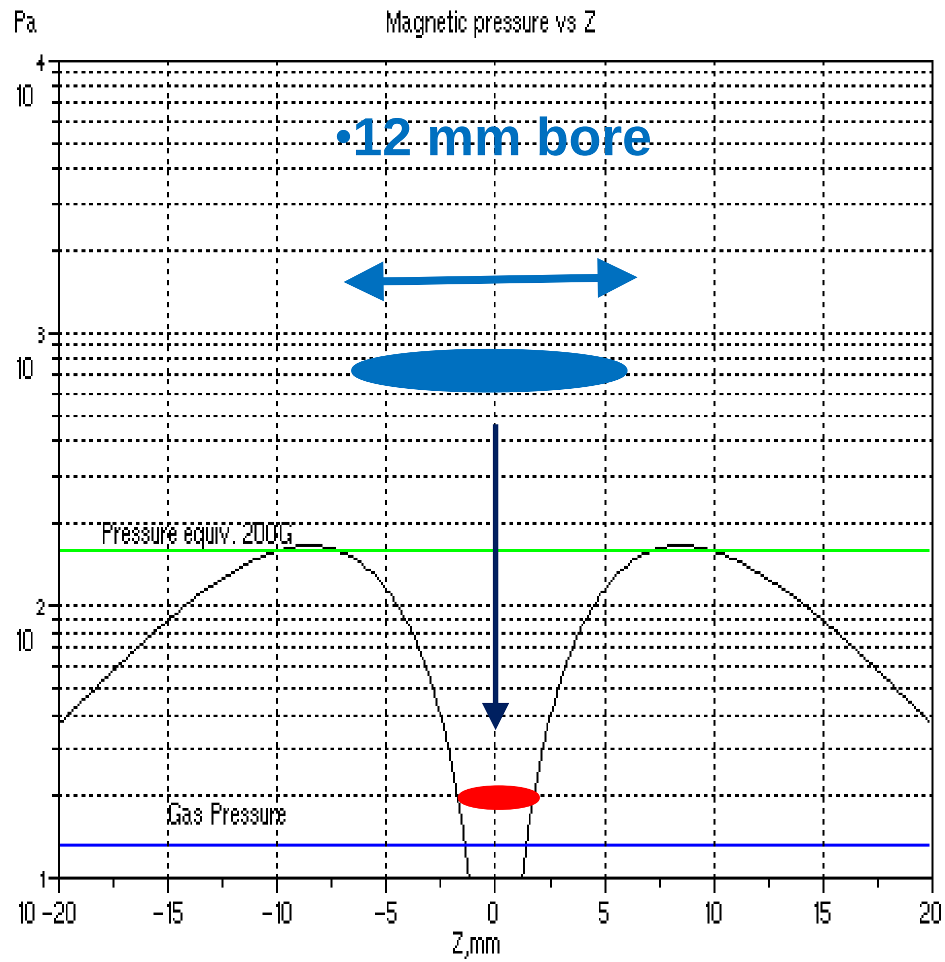




Six magnet assemblies; similar poles inward facing creates a modified spindle cusp.

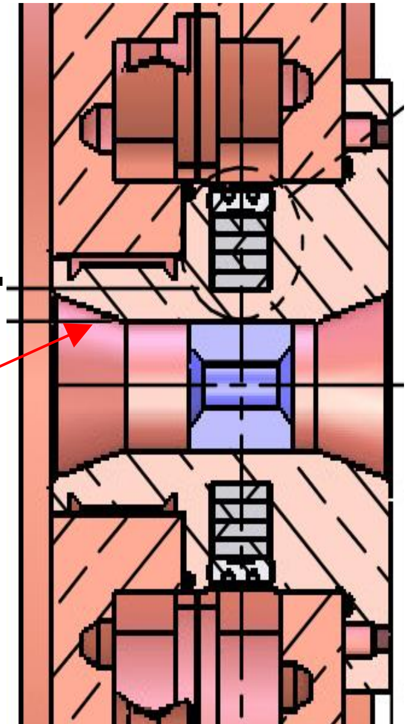
Axial magnetic pressure profile

- Three magnets in 6 positions produces ~ 10X neutral gas pressure at +/- 8 mm
- Desired result…
- Should be plenty of field to see any effect.

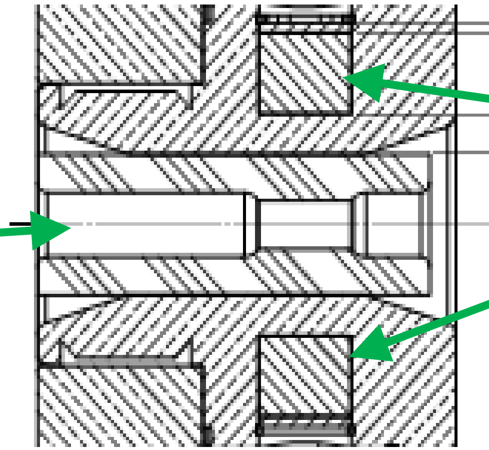


First attempt… 3 x 6 magnets, standard bore

- Source would not operate.
  - Magnets somehow caused plasma-bore arcing.
  - Removing the magnets restored normal operation.
  - Concept was abandoned for the moment.
- Second attempt –full length SiC bore
- Shield the copper from the plasma.. .



Full length silicon carbide insert



Start with two magnets, not three

Main results – unexpected shift in operating point.

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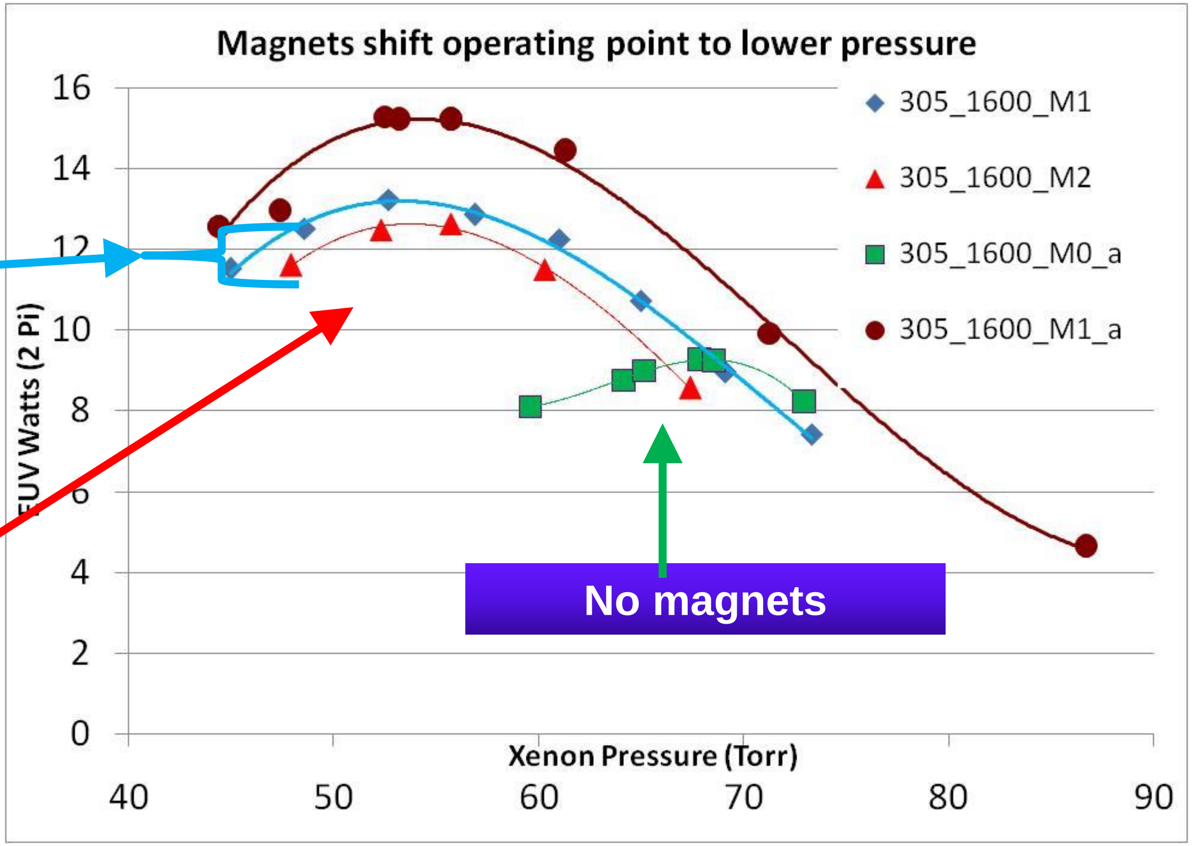

One magnet: Power increases ~ 60% over no magnets

Two magnets: Cannot see cusp in visible or x-ray light

No magnets

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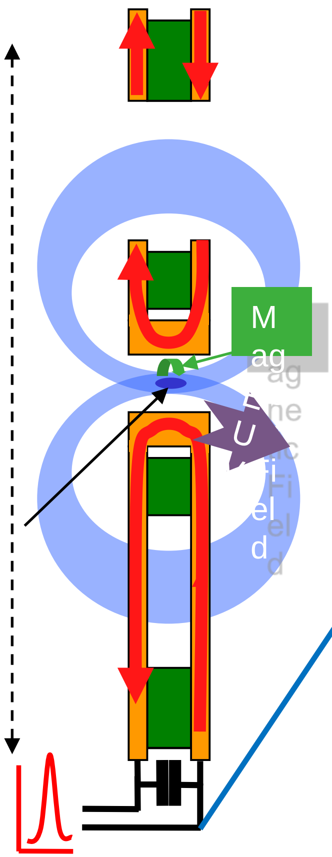
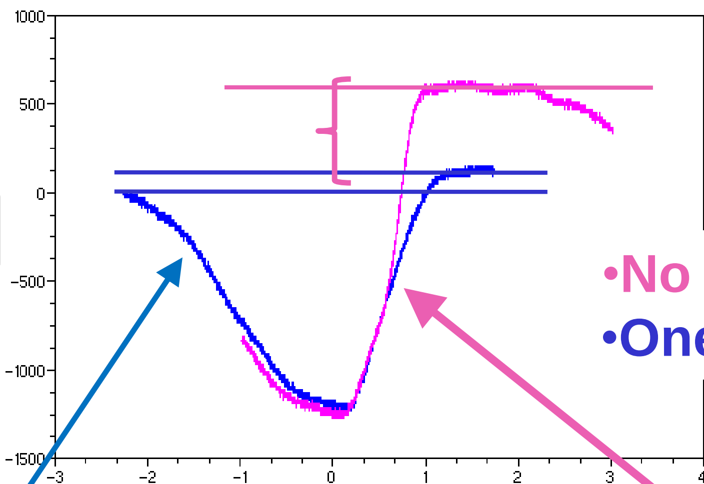
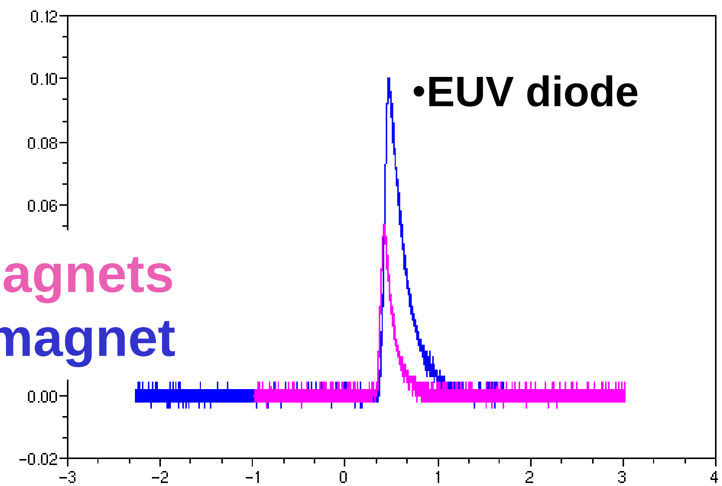
Magnetic field allows more efficient operation at low pressure





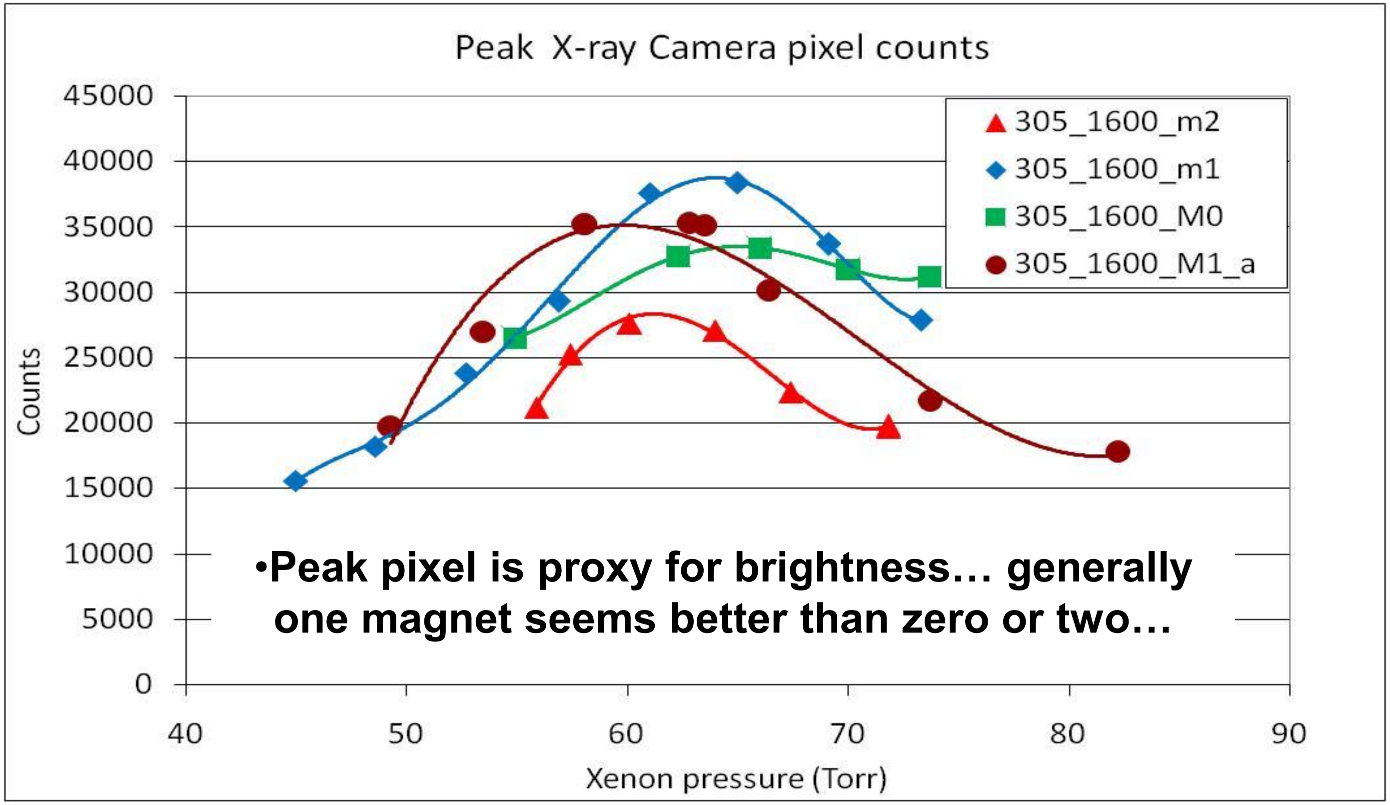


- No magnets
- One magnet

- Reflected voltage – energy not consumed by plasma

- Possible arc?

Brightness data shows weaker effect

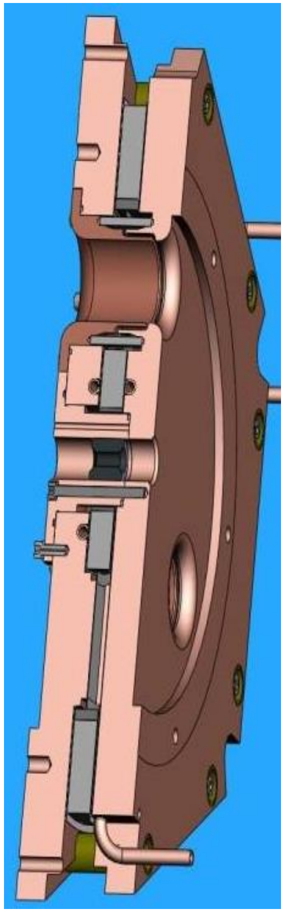


Conclusions

- The cusp field was supposed to shorten the plasma.
  - No effect was seen
- Power, brightness data agree one magnet is better than zero or two
- **Main effect – seen – shift to lower pressure operating point**

- **Possible explanation – E ll B?**
  - Electric field E – Curl **E ~ dB/dt** in induction core
  - Magnetic field B – Curl **B ~ J**; **J** looks like a surface current on the same core
  - Geometry of **B,E** fields should be very similar.
- Could provide very efficient electron confinement, leading to higher electrical efficiency, new operating point.

- **Might be a path to exploit in commercial source…**



Thank you!